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Four years of experience with a permanent seismic monitoring array at the Ketzin CO2 storage pilot site

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Abstract

CO_2 was injected into a saline aquifer near the town of Ketzin in Germany from July 2008 to August 2013. To monitor CO_2-migration close to the injection well, TNO installed a fixed 2D seismic array of 120 meters length in 2009, with 3- component (3-C) geophones at the surface, 4-component receivers at 50 meters depth and a central vertical array of 4-component receivers. The test-bed is used both for the recording of high-quality active time-lapse seismic data as well as for continuous passive seismic data recording. Here we focus on the latest results obtained from active source experiments, micro-seismic data analysis and ambient noise seismic interferometry (ANSI) of passive seismic data.

Data from two experiments with a source driven by linear motors (permanent) and an impact hammer source (semi-permanent) were evaluated in order to assess the repeatability of the two source types.The repeatability of the first source was relatively high compared to the second source. After the stop of injection in August 2013, active seismic shots were acquired repeatedly on a daily basis. These data did not show significant impedance changes at reservoir level. Microseismic event analysis of passive seismic data detected a few local events originating from reservoir depth. In order to quantify these events the seismic array was successfully calibrated by using independent earthquake recording. This yielded estimates of the local magnitude for local events within the range [-2.5,0.5]. Recent work on ANSI focused on the application of this method on both synthetic and field data. The resulting reflection response shows a strong resemblance with outcomes from active shot reflection profiles, and the key reflectors at reservoir level have comparable characteristics.

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Keywords: Seismic monitoring; Passive seismics; Continuous monitoring; Permanent array; CO_2 aquifer storage; Time-lapse seismic; Seismic noise interferometry; Ketzin; ANSI

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1. Introduction

At the CO_2 sequestration site near Ketzin, Germany, CO_2 injection started in June 2008 [1], and a total of 67.271 t CO_2 was injected until the cease of injection in August 2013. A large variety of geophysical techniques have been tested during this period at the Ketzin site. Figure 1 shows an aerial view from the Ketzin site with locations of injection- and observation wells, as well as the location of the permanent seismic array that was installed by TNO in 2009. Here we focus on the latest results of the data-analysis of both active and passive data acquired with this array, which consists of vertically and horizontally aligned geophones and hydrophones situated in a vertical plane [2]. Both active and passive seismic data have been recorded since the installation of this array. More than four years of recording and experimentation have resulted in a vast and rich data set providing an excellent opportunity to develop and test innovative approaches aimed at characterization and monitoring of the subsurface during CO_2 injection [2,3].

Here, we report on the development of three approaches aimed at monitoring the effects of pressure and velocity changes resulting from CO_2 injection at the Ketzin site: (1) permanent active source seismic data analysis, (2) passive microseismic event analysis, and (3) ambient seismic noise interferometry. Section 2 presents the results of a comparison of the source repeatability of two source types to assess their performance. Passive microseismic event analysis focused on magnitude estimation of seismic events, based on the calibration of the seismic array by using independent earthquake recordings. Results are shown in section 3. Finally, section 4 describes the outcomes of ambient seismic noise interferometry for retrieval of reflected P-waves conducted on both real and synthetic noise data.

1.1. Geology

The Ketzin CO_2 storage site is located at the southern flank of a gently dipping anticline, which formed above a salt pillow situated at a depth of 1500–2000 m. The target formation for CO_2 injection is the Stuttgart Formation of Triassic age, located at approximately 650 m depth. The Stuttgart Formation is on average 80 m thick and lithologically heterogeneous: sandy channel-(string)-facies rocks with good reservoir quality alternate with muddy, flood-plain facies rocks of poor reservoir quality [4,5].

The thickness of the sandstone interval may attain several tens of meters where sub-channels are stacked. The top seal of the Stuttgart Formation is the Triassic Weser Formation. The Weser Formation, deposited in a clay/mudsulfate playa environment, consists mostly of mudstone, clayey siltstone, and anhydrite as observed on well logs and on 30 m core obtained in the CO_2 Ktzi 200 and CO_2 Ktzi 201 wells [6]. The top of the Weser Formation is a 10 to 20 meter thick anhydrite layer generally referred to as the K2 reflector, situated about 70 meters above the reservoir. This reflector is very clear on 2D and 3D surface seismic data [7].

1.2. Layout of the permanent seismic monitoring system

TNO designed and implemented a permanently installed seismic monitoring system [8], which is used for both passive and active seismic observations. Passive seismic data acquisition started in fall 2009, resulting in continuous recordings that span a period of more than four years. The array contains 13 3-C geophones with a co-located hydrophone buried at 50 m depth as shown in Figure 1. The total length of this array is 120 m. At seven locations above this buried 2-D line 3-C geophones were installed at the surface. An additional five 3-C geophones and hydrophones were placed in a vertical borehole at 10 m depth intervals at the center of the buried 2-D line [2,9].

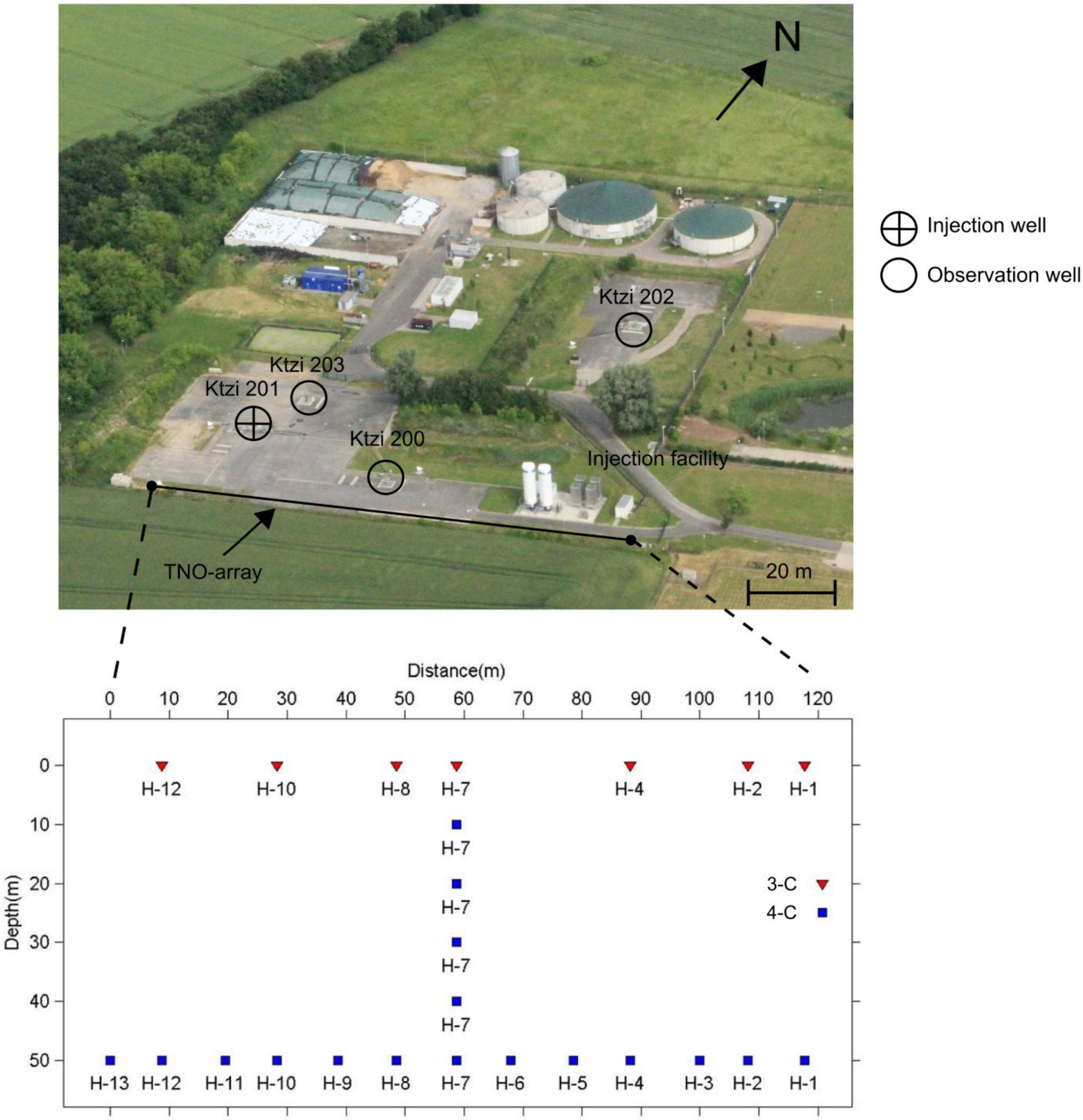

Fig. 1. Top: Aerial photograph of Ketzin with indication of locations of injection- and observation wells and positions of the TNO array (Courtesy of GFZ). Bottom: Lay-out of the Ketzin array.

2. Permanent active source seismic data analysis

In total four active source seismic surveys were acquired with the permanent array in the period of CO_2 injection: two active source repeat surveys [2,9], and two experiments with a permanent seismic source and a semi-permanent source, respectively. Here, we focus on the results obtained by the latter two experiments.

The two experiments with permanent seismic sources were respectively conducted during a temporary halt of CO_2 injection in May 2012, and after termination of the CO_2 injection in August 2013. These experiments were set up to demonstrate that the use of a permanent source can enhance the repeatability of active seismic measurements significantly. The first permanent source survey was conducted from May 4th to May 29th 2012. During that time the source was used for 1 hour per day [9]. The used source is a highly innovative prototype vibroseis source driven by linear motors under development at the Technical University of Delft [10,11,12]. The second survey was carried out with a semi-permanent impact hammer source after the termination of the CO_2 injection from August 24th – August 27th 2013. One of the goals of the second survey was to detect anticipated acoustic impedance changes at reservoir depth due to pressure changes that would result from the ceasing CO_2 injection. However, data analysis did not indicate significant changes in amplitude response of the key reflectors at reservoir depth.

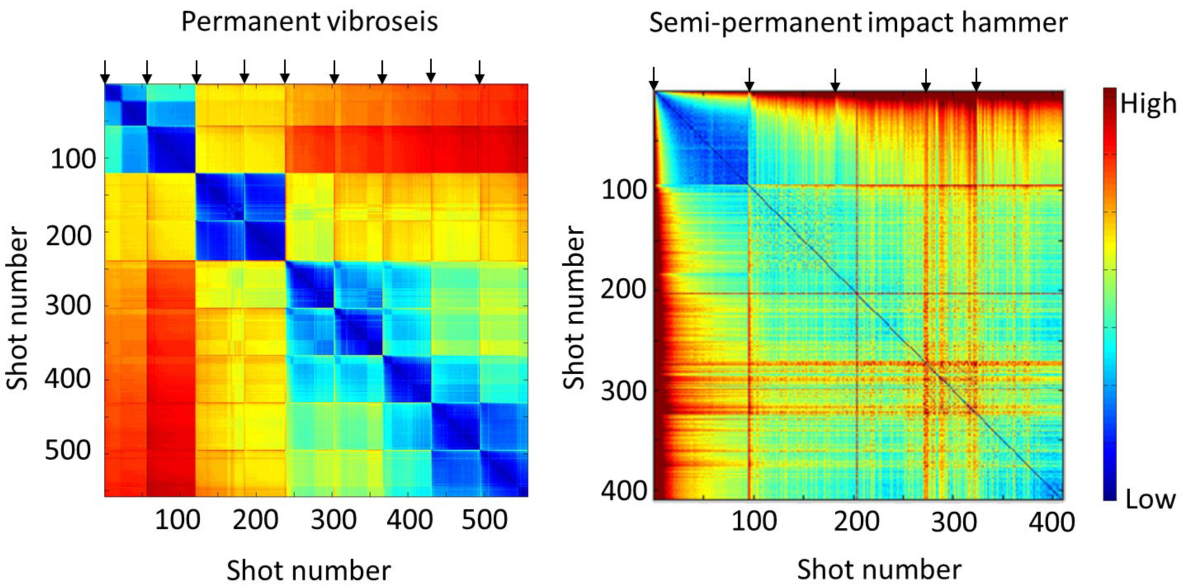

Fig. 2. Relative quantification of the difference of the shot data with a reference shot within a certain time interval, which we call the power of difference comparison. Each shot is compared to all others by calculating the mean of the absolute values of the difference between each shot and all others. Left: Power of difference for the active survey performed in May 2012 in window 0-350 ms. Right: Power of difference for the active survey performed in August 2013 calculated in time window 150-250 ms. The arrows mark the onset of a measurement repeat period; 9 repeat periods in May 2012 (left) and 5 repeat periods in August 2013 (right).

We compared the results of the two surveys in terms of repeatability of the source signatures of the two source types. This is illustrated in Figure 2 showing the power of difference (POD) plots for the first and second survey at the left and right respectively. The POD plots show the variability of the data within a certain time interval. Each shot is compared to all others by calculating the mean of the absolute value of the difference between each shot and all others. So the plots are symmetric around the diagonal extending from top left to bottom right, where the POD is 0 (i.e. each shot is subtracted from itself). Along the horizontal and vertical direction the mutual difference between shots are shown. The POD shown in Figure 2 is calculated in time windows (<350 ms) above reservoir level (~500-530 ms, in raw prestack data for the deep array), so we only look at signal repeatability and exclude effects from

CO_2 injection at reservoir depth. The arrows at the top indicate the start of a new measurement repeat period, which took approximately 1 hour per repeat period (respectively 9 and 5 repeat periods for first and second survey). From Figure 2 we can observe for the first survey a relatively stable POD with slight decay within individual repeat periods, indicating a relatively high repeatability of the source signal (Figure 2 left: uniform colors) with a minor decay in source signature response during a single repeat period (Figure 2 left: note gradual color change from bottom left to top right within a single cell). The observed gradual change during a repeat period is probably related to instrument heating effects. The second survey shows a relatively unstable POD within individual repeat periods pointing at a relatively low repeatability of source signal (Figure 2 right: colors fluctuate from red to blue). Clear jumps in POD are observed between several successive repeat periods for both the first and second survey reflecting temporal changes in source coupling and site conditions, such as background noise and soil moisture. These results show that the permanent vibroseis source yields data of a higher repeatability than the semi-permanent hammer source.

3. Passive microseismic event analysis

Since September 2009 passive seismic data have been recorded continuously using the permanent array, with a sample rate of at least 2 ms. This has resulted in a dataset of 35 terabytes of data up to now. A procedure has been developed to automatically detect and locate very low magnitude seismic events [3,13]. The procedure consists of three main steps: (step 1) A quality control step, (step 2) a noise suppression and event picking step and (step 3) an event localization step. The approach is completely data-driven.

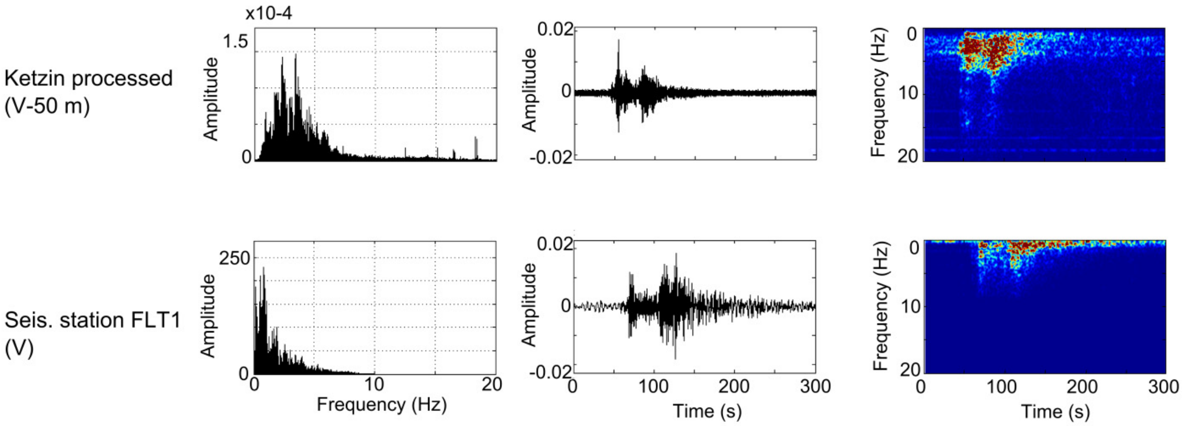

Fig. 3. Comparison between an earthquake recorded on vertical component data of Ketzin (top) and nearby seismological station data (FLT1). From left to right frequency spectrum, trace data and time-frequency plots.

The microseismic data analysis resulted in the identification of a small number of weak seismic events originating from the reservoir depths. We have been developing and testing approaches for obtaining magnitude estimates for these events. Our method relies on the use of an empirical calibration function that relates magnitude estimates obtained from recordings of earthquakes with broadband seismometers to the recordings of the same earthquake on our array in Ketzin. We performed a detailed analysis for a few earthquakes with epicentral distances between 150 and 400 km from the Ketzin site. We retrieved the recordings of nearby (about 60 km to 200 km) stations that are part of a regional seismological network. The earthquakes that we used in the analysis had reported local magnitudes in range between 3.0 and 4.3 and occurred within 250 km distance from the Ketzin array. Four seismological stations were selected which are spaced 60-190 km from the Ketzin array. Earthquake recordings were used that were both recorded on the Ketzin array and on the seismological stations. We found that, after harmonizing the frequency content of the data, the earthquake waveforms observed in the seismometer- and geophone recordings are quite similar, although some differences in signal characteristics are observed. This is also illustrated in Figure 3, showing an earthquake that occurred on February 20th 2010 with a local magnitude of 4.3, being recorded on both the Ketzin array (top) and on a nearby broadband seismometer (bottom). From left to right we see the frequency spectrum, trace data and time-frequency plots. A difference between the two datatypes is that the frequency content of the Ketzin recording extends beyond 10 Hz (top right), whereas the station recording contains frequencies below 1 Hz, which is due to the frequency characteristics of the receivers. In this respect the two datatypes might be used complementary.

By calculating signal attributes on a selection of earthquakes, regression relationships between local magnitude value and signal attributes were set up within the range M_L=[3,4.3]. Next, these relationships were extrapolated downwards for seismic events originating from a depth interval containing the reservoir layer. Initial estimates demonstrate M_L=[-2.5,0.5] for these local events.

4. Ambient noise seismic interferometry

A recent seismic technology development retrieving passive seismic reflection data is the application of ANSI [14,15,16]: noise registrations continuously measured over a long period of time are correlated with each other to produce P-wave reflection data as if these were generated by active seismic sources at the surface. We tested the feasibility of using this technique for the purpose of subsurface characterization, both on numerically generated noise [18] and on ambient noise field data. However, a comparison between a base case (i.e. the situation before injection) and a repeat case (i.e. a monitoring result) passive survey could not be produced, because the CO_2 plume had already passed below the Ketzin site once data recording started with the seismic array. Therefore the initial objective was adapted to at least demonstrate that ANSI applied to noise recorded in Ketzin would provide useful P-wave reflection information, from which a structural image of the subsurface can be obtained. Additionally, ANSI was applied in time-lapse mode on synthetic noise data to assess the suitability of this method for monitoring migration of the CO_2 plume in the subsurface at the Ketzin site.

Figure 4 shows a comparison of reflection profiles extracted from active source data and from autocorrelation of ambient noise, for both field data and synthetic data [17]. Figure 4a presents results of a field data stack using an active source at the surface and vertical component geophones buried at 50 m depth. Figure 4b shows autocorrelation results using one day of noise recorded by these geophones. The autocorrelation panel obtained from synthetic noise data is given in Figure 4c with both the virtual source and geophones at 50 m depth. Figure 4d highlights the synthethic active source response for a source at 50 m depth. The location of the K2 reflector is marked as a green line and is clearly recognizable at approximately the same time on the four panels. The correspondence in the retrieved arrival times of this key reflector is an indication that ANSI provides scope for the purpose of subsurface characterization. It should be noted that results shown in Figure 4b were obtained from data recorded during a day that included a relatively large amount of (nearly) vertically incident P-waves compared to other days, making it more suited for application of ANSI with the seismic array. Also, based on current observations of data recorded after the start of injection by the seismic array, no significant temporal variations could be identified within the seismic data at reservoir depth. This suggests that the CO_2 saturation during the monitoring period was relatively constant compared to the situation before CO_2 injection.

Finally, results obtained from ANSI applied on synthetic ambient noise data applied in time-lapse mode including the situations before and during CO_2 injection, suggest that significant time-lapse effects at reservoir level from CO_2 injection can be observed, when both the base case (prior to injection) and the repeat case (during injection) are compared [17].

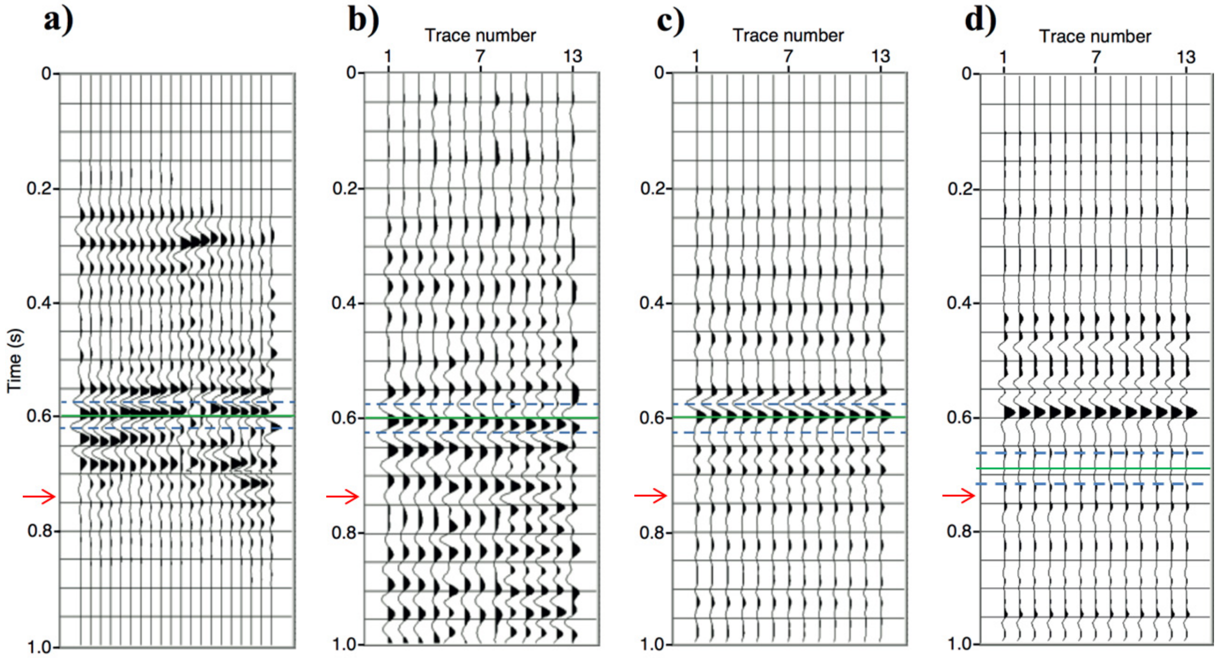

Fig. 4a) Ketzin field data stack profile using active sources at the surface. b) Autocorrelation result using one day of noise recorded on the vertical component of the geophones. c) Autocorrelation panel obtained from modeled data for the vertical component of the geophones. Panels a), b) and c) are filtered to the same bandwidth. d) Active-source modeled response for a source at 50 m depth. The geophones for all cases are at 50 m depth. Candidate location of K2 reflector is indicated as a green line. The red arrow marks the location of the top of the Stuttgart formation as observed from active seismic data. Figure from [17].

5. Discussion and conclusions

Both passive and active seismic data were recorded with a permanent array at the Ketzin CO_2 storage demonstration project site in Germany, covering a period for over 4 years. The recordings were used to obtain high-resolution reflection information from active source surveys, to detect micro-seismicity and to retrieve reflection profiles from ANSI.

We compared data acquired with two different types of (semi)permanent sources to assess the repeatability of the source signature of the two instruments. The first test was conducted with a true permanent source developed by TUD, and centered around a period where injection stopped. The second experiment was conducted directly after cease of CO_2 injection in August 2013 with an impact hammer source repeatedly hammering at a fixed location. In general, the repeatability of the first source was relatively high compared to the second source. Still, both day-to-day and intra-day variations in seismic response occurred for both source types, possibly caused by changes in ground coupling, instrument- and soil conditions. Results from the second semi-permanent source survey (after stop of the injection) do not point at an anticipated amplitude change at reservoir depth that might have been expected after cease of CO_2 injection (pressure variation).

Concerning the passive seismic data analysis, the array is suitable for the detection of weak seismic events. Recent work focused on the quantification of local seismic events by calibrating the seismic array using independent earthquake recordings. Regression relationships were established between signal attributes and local magnitudes of earthquakes recorded by both Ketzin array and seismometers. From this we calculated estimates for local events ranging from M_L=[-2.5,0.5]. More accurate estimations may be obtained by including more earthquakes into these relationships.

The latest results of ANSI applied to synthetic data from Ketzin support the idea that monitoring the migration of injected CO_2 using continuously recorded noise should be feasible in a geological setting and with noise conditions comparable to the Ketzin case. In addition, this ANSI – study, performed on ambient noise recorded in Ketzin, demonstrates the feasibility of producing a reflection image from body wave noise.

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